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Road dust load dynamics and influencing factors for six winter seasons in Stockholm, Sweden

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HIGHLIGHTS

- There is a seasonal dependency in road dust loads in Stockholm.
- The lateral road dust load variation is high.
- Road dust load is depending on road surface properties.
- Repaving of a street resulted in markedly increased dust loads.
- The wet dust sampler (WDS) is a useful tool for total dust load follow-up studies.

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ABSTRACT

Traffic related non-exhaust particulate sources and road dust are an increasingly important source for PM_{10} air pollution as exhaust sources are decreasing due to regulations. In the Nordic countries, the road dust problem is enhanced by use of studded tyres, causing increased road wear and winter road maintenance including gritting. Efforts to reduce road dust emissions requires knowledge on temporal and spatial road dust load dynamics. The city of Stockholm, Sweden, has therefore financed seasonal (October to May) road dust sampling to be able to optimize their winter and spring time street operation measures for reduced road dust emissions. This work describes the outcome of six seasons (2011/2012–2016/2017) of road dust sampling in five central streets using the VTI wet dust sampler (WDS).The results show that road dust load, expressed as DL180 (dust load smaller than 180 µm) has a seasonal variation with the highest loads (up to 200 g/m^2) in late winter and early spring and a minimum (down to about 15 g/m^2) in early autumn and late spring. The dust load varies between streets and is depending on pavement surface properties. On a smaller scale the dust load has a high variability across streets due to differences in rates of suspension from different parts of the road surface, with low amounts in wheel tracks and higher in-between and outside the tracks. Between 2 and 30% of the DL180 is smaller than 10 µm and could directly contribute to PM_{10} emissions. In general, higher road surface texture leads to higher dust loads, but the condition of the pavement (e.g. cracks, aggregate loss) might also have an effect. A new, wear resistant pavement accumulated markedly higher road dust amounts than a several years old pavement. This paper closes with a discussion on the complex relation between road dust load and PM_{10} concentrations and a discussion on the challenges and comparability of road dust sampling techniques and measures.

1. Background

Non-exhaust particles from road traffic have been noticed as an increasingly important source to air pollution, since traffic globally is increasing and emissions from non-exhaust sources, like tyre, break and pavement wear, are subject to few international regulations (Amato et al., 2014b; Denier van der Gon et al., 2012). Non-exhaust emissions will also be important in the future even if the vehicle fleet would be completely electrified (Timmers and Achten, 2016). Except from being emitted directly to the air, non-exhaust particles deposit and

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accumulate, together with dust from other sources, on road surfaces to form road dust. The dust is suspended by traffic and/or wind and contributes to air pollution. The sources to road dust differ widely both geographically and temporally (Amato et al., 2012, 2014a, 2014b; Chen et al., 2012; Etyemezian et al., 2003; Fujiwara et al., 2011; Kuhns et al., 2005; Pirjola et al., 2010; Zhu et al., 2008). Common traffic generated sources are, as mentioned, brake and tyre wear particles (Denier van der Gon et al., 2012; Garg et al., 2000; Gietl et al., 2010; Grigoratos and Martini, 2014; Hulskotte et al., 2007; Lee et al., 2013; Panko et al., 2013; Sanders et al., 2003). Road operation measures (traction sanding, salting) and pavement wear from studded tyres are also common sources and in some Northern countries during the winter season (Gustafsson et al., 2009; Kupiainen and Tervahattu, 2004; Kupiainen et al., 2016; Kupiainen and Pirjola, 2011). . Traction sanding can contribute both by containing and being ground into fine, suspendible dust, but also through contribution to pavement wear through a grinding effect on pavements. This is referred to as the sand paper effect (Kupiainen et al., 2003). Dust from surrounding areas, like farm land, deserts, building sites and gravel roads all differ widely depending on geography, climate and time of year.

Since road dust accumulates on the road surface, the surface properties are important for subsequent emissions. Road dust accumulation depends mainly on surface macro texture (commonly Mean Texture Depth, MTD, or Mean Profile Depth, MPD) that affects both the amount of dust accumulated and how available this dust is for suspension by traffic. Studies by China and James (2012) and Blomqvist et al. (2013) show that for the same dust load and suspension force, a coarser macro texture (expressed as MTD) will emit lower amounts of suspended particles. Studying the total amount of accumulated dust below 180 μm (DL180) in the surface texture, Blomqvist et al. (2013), showed that, in real city street environments (in Stockholm, Sweden), DL180 generally increased with increasing macro texture. In a real road environment, the volume, composition and speed of the traffic, as well as meteorological factors, will influence the accumulation and suspension (Denby et al., 2013a; Denby et al., 2013b; Norman et al., 2016). Simultaneously, these factors will also influence the source strength of non-exhaust, as well as exhaust, particles, and the resulting dust load will be the result from a balance between accumulation and suspension. A crucial meteorological factor is road surface moisture, which has been proven to strongly affect the emission of dust (Denby et al., 2013a; Johansson et al., 2007). In Stockholm, Sweden, where PM10 levels are strongly influenced by road dust emissions, an almost perfect anti-correlation can be seen with road surface moisture (Norman and Johansson, 2006). Suspension of dust is strongly reduced on moist streets. In the NORTRIP (NOn-exhaust Road Traffic Induced Particle) emission model, developed as a physically based non-exhaust particle emission model, special efforts have therefore been made to describe and account for road surface moisture (Denby et al., 2013a).

In Sweden, road dust related PM10 is an important cause for exceedances of the EU limit values (Areskoug et al., 2001). Mainly, confined city streets with high traffic amounts have had problems reducing the PM10 concentrations. As a result of these findings, research was directed towards understanding the emission processes and how to abate them. In laboratory experiments, Gustafsson et al. (2009) concluded that studded tyres produced tens of times higher PM10 emissions than non-studded winter tyres. In parallel, research in Norway and Finland pointed out studded tyres and winter sanding as important sources (Kupiainen, 2007; Snilsberg, 2008). As a result of this scientific evidence, abatement measures in the Nordic countries have been focussing on how to reduce PM10 emissions from road dust. These include e.g. reduced use of studded tyres, reduced speed, improved road sweeping and dust binding.

Few studies have investigated the influence of road operational measures on PM10 emissions. Amato et al. (2010) made a review of the effects of sweeping and concluded that, even though literature was scarce, road sweeping alone had not been shown to reduce PM10 concentrations in short term studies. Combined with water flushing, sweeping has a better reduction potential. The few studies on using dust binding agents on paved roads generally showed a high potential for short term PM10 reduction. Especially in cool climates, dust binding seems to be effective. For instance, Norman and Johansson (2006) showed that PM10 in a Stockholm street could be decreased by up to 35% using CMA (calcium magnesium acetate). Gustafsson et al. (2010) showed similar results also for MgCl2, CaCl2 and sugar solutions. Amato et al. (2014c), on the other hand, showed that dust binding of paved roads in warm climates, are not effective. In the study made in Barcelona, neither CMA nor MgCl2, could be shown to have a significant effect. The authors concluded that the rapid drying-up of chemical dust binders in high temperatures and the low amounts of road dust accumulated were important factor influencing the results.

The city of Stockholm has the most abundant PM10 problems among Swedish cities and there is epidemiological evidence that especially the coarse fraction of PM10 is significantly associated with both mortality and morbidity of the population (Meister et al., 2012). In 2005, an abatement plan to reach the EU limit values was adopted that included specific abatement measures (Länsstyrelsen i Stockholms län, 2004) against road dust and its' suspension. Use of CMA as dust binder and extra sweeping with a special vacuum sweeper operating without water application are the main road dust mitigation measures together with a ban of studded tyres on certain streets (Norman and Johansson, 2006; Norman et al., 2016). To follow up the effects of the Stockholm dust mitigation measures, the changes in road dust load during the winter season have been studied. This paper summarises the results and experiences during the first five seasons of this work.

2. Methodology

2.1. Site description

Stockholm is situated close to the Swedish Baltic coast where the lake Mälaren connects to the Baltic sea (59°19′46″N 18°4′7″E). It has a humid continental climate with distinct seasons, including cold, snowy periods in winter. The number of inhabitants is about 950 000 (Stockholms stad, 2017).

Road dust load was sampled at, or in close proximity to air quality monitoring stations in the Stockholm city centre (Fig. 1). The streets have different characteristics (Table 1); Hornsgatan, Sveavägen, Folkungagatan and Odengatan have four lanes (two in each direction), Fleminggatan two lanes (one in each direction), Norrlandsgatan two lanes in the same direction. The traffic amounts were 5467–23 800 vehicles per day and the pavements are stone mastic asphalts (SMA) with generally wear resistant rocks such as quartzite, granite and porphyry, with varying maximum aggregate sizes (11–16 mm). Four sites (Sveavägen 59, Hornsgatan, Folkungagatan and Norrlandsgatan) were used during all years, Sveavägen 83 from spring 2013, Fleminggatan in spring 2013 and from autumn 2015 to spring 2017 and finally Odengatan from autumn 2013 to spring 2015. All sites have 4–5 story buildings on both sides of the road but have different street canyon widths.

2.2. Road dust load sampling and analyses

Road dust load was sampled using the VTI Wet Dust Sampler (WDS, Fig. 2, Jonsson et al., 2008; Lundberg et al., 2019), which is a sampler using high pressurized water to clean a small circular road surface area during a specified time and compressed air to move the sample from the washing unit to a sample bottle. Each washing is referred to as a "shot". The washing unit uses a spray nozzle with a filled cone spray pattern to thoroughly clean the surface. Two sampling strategies were used: either six "shots" were collected in one large bottle as one sample to even out variation at short distances of the road, or each "shot" was collected individually. The six-shot samples were collected three after one

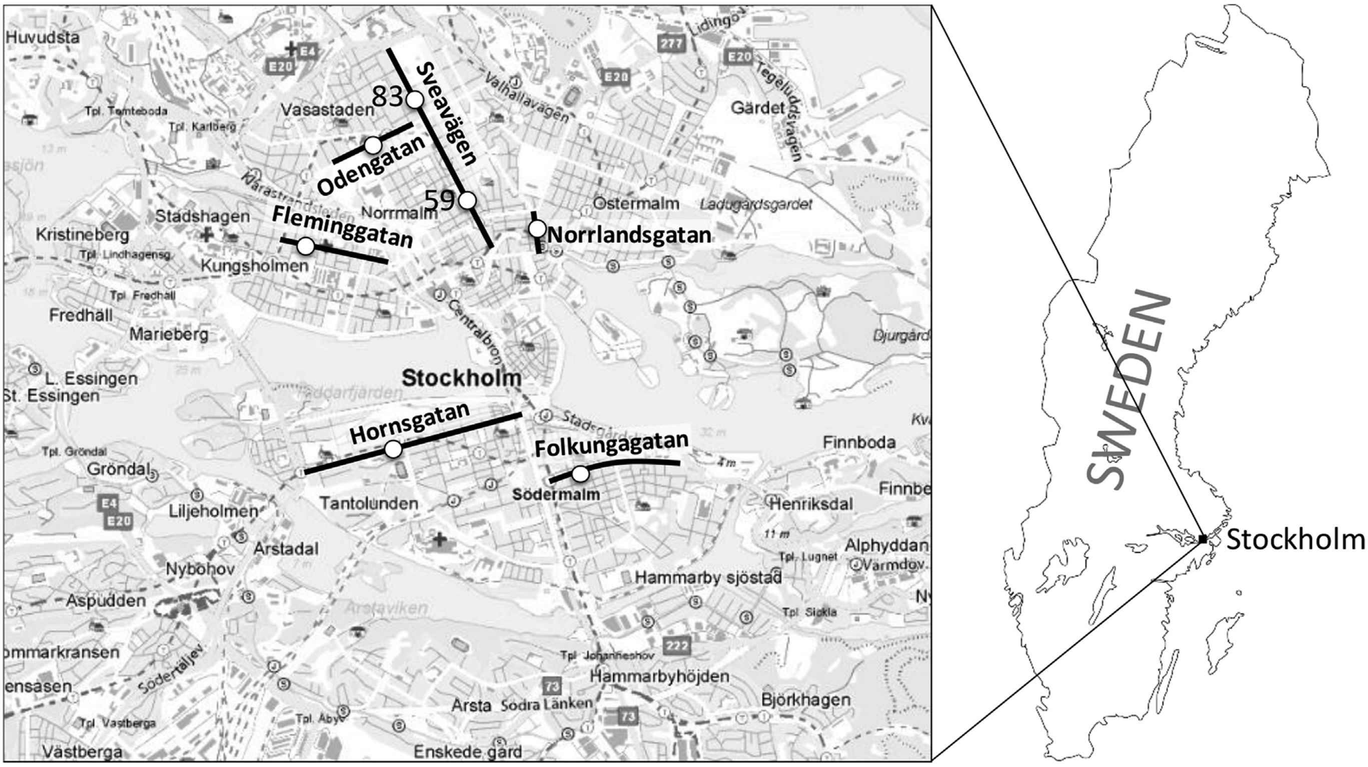

Fig. 1. Central Stockholm with investigated streets. White dots indicate positions of air quality monitoring stations.

Table 1
Description of the measurement sites.

Street	Traffic (ADT)[a]	# of lanes	Texture[b] (MTD, mm)	Direction (main)	Pavement type
Hornsgatan	23 800	4	1.5/2	E-W	SMA16
Sveavägen 59	23 400	4	1.3/1.1	N–S	SMA11
Sveavägen 83	18 068	4	–	N–S	SMA11
Folkungagatan	15 100	4	1.7/1	E-W	SMA11
Fleminggatan	19 100	2	–	E-W	SMA
Norrlandsgatan	7600	2	1.2/0.9	N–S	SMA
Odengatan	5467	4	–	E-W	SMA

[a] Vehicles per day, Data from 2014.
[b] Wheel track/between wheel tracks.

another at two distances from the road side, in the left wheel track (WT) and between wheel tracks (BWT), see Fig. 3. This strategy was combined with sampling individual "shots" to get a picture of the lateral distribution of road dust, consisting of a transect of single shot samples from the curb across the parking area or cycle path and across the rightmost driving lane (Fig. 3).

The WDS has been used in several Swedish national research projects, mainly for investigating the influence on different street and road operation measures against road dust emissions (Gustafsson et al., 2011, 2012, 2014, 2015, 2016, 2017; Janhäll et al., 2016; Järlskog et al., 2017), and has recently been exported to Finland and Norway which will increase the availability of comparative studies.

Even though the WDS sampler has a theoretical maximum cut-off at 5 mm, which is the diameter of the outlet from the sampling chamber, particles of that size on the road surface are not directly relevant for air quality. From standard sieving methods the mesh of 180 μm was chosen for analysis as it removes the larger particles from the sample reducing variability due to few large particles that is large enough not to be emitted to the air, but still include most particles that would affect air quality even at shorter distances from the road. The NORTRIP-model (Denby et al., 2013a,b), developed to calculate the PM10 contribution from streets including road dust and other non-exhaust particles, road dust load is defined as road dust finer than 200 μm, i.e. close to the 180 μm chosen for sample sieving. The samples were then filtered using Buchner funnels with Munktell 00H filter paper. The filters were burned at 550 °C and the inorganic amount of the sample determined. The dust load is called DL180, being the inorganic fraction of dust smaller than 180 μm. One of three bottles sampled between wheel tracks were used for out-takes to size distribution analyses using a laser granulometer (Between, 2011 and 2014 a CILAS and between 2014 and 2017 a Malvern Mastersizer 2000). From the cumulative size distribution, the fraction of DL180 being smaller than 10 μm can be calculated (DL10). DL10 might be of closer interest when comparing dust load to PM10 concentrations.

Sampling in and between wheel tracks was performed at 6–8 occasions each winter season, normally between October and May, when the extra PM10 road operations were in practise. Transects of single shots was performed occasionally during the measurement period.

2.3. Macro texture – sand patch

The road surface macro texture, as an indication of the road surface ability to store dust, was measured using the volumetric, contact method commonly known as the sand patch method (EN 13036–1:2010). A pre-defined amount of fine glass beads (90% between 180 and 250 μm according to ISO565) is placed in the middle of the surface of interest and spread out into a circle shape using a hard rubber puck until it cannot be further spread. The diameter of the circle is measured in four equally spaced directions and a mean value calculated and used to further calculate the mean texture depth (MTD). The method is operator sensitive. For this reason, the same person performed all measurements.

MTD was measured in left wheel track and between wheel tracks on the four streets Hornsgatan, Folkungagatan, Sveavägen and Norrlandsgatan in spring 2012. This is the period in Sweden when macro texture is normally highest, after the winter when studded tyres

Fig. 2. The VTI wet dust sampler (WDS II). Front view (left) and sampling in a city street (right).

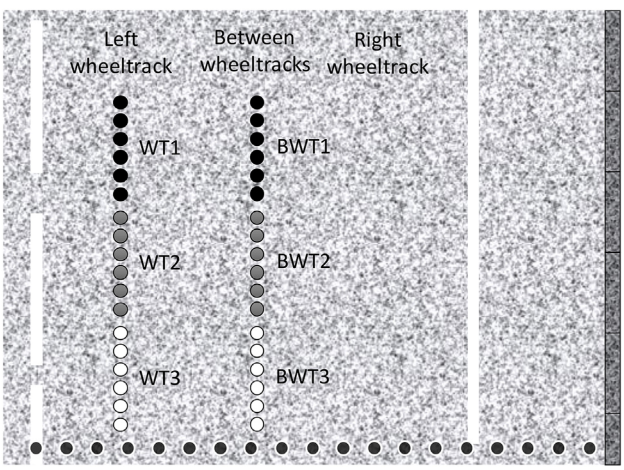

Fig. 3. Used WDS sampling alternatives. Sampling three large bottles in left wheel track (WT1–3) and in-between wheel tracks (BWT1–3) and a profile from the kerb over the first driving lane (bottom line of dots).

are used. During summer and early autumn, texture decreases as non-studded tyres polish the surface (Jacobson, 2005). Data is lacking from Fleminggatan, Odengatan and from the new pavement laid on Folkungagatan in 2016.

3. Results

3.1. Road dust annual cycle and variation between streets

Road dust load (DL180) is highly variable in time and space. In Fig. 4, the mean values of seven locations in WT and BWT during six winter seasons are shown. DL180 is generally highest from mid-winter to early spring and lowest in early autumn and late spring. Separated into street locations and seasons (Fig. 5), the highest dust loads were measured between wheel tracks on Hornsgatan and in wheel track on Folkungagatan during the first season of measurements (2011–2012). Comparing the pavements revealed that these specific surfaces were more damaged (mainly cracks and aggregate losses) than other surfaces. Therefore, the tests were moved to undamaged parts of the same pavements the following seasons.

During each winter season (September–May) the pattern is similar on all streets; low road dust loads in the beginning and at the end of the season and obvious peaks from midwinter to early spring. Maximum values of DL180 on different streets vary between 15 and around 200 g/m2. The difference between WT and BWT differs between streets. On Hornsgatan, Sveavägen and Fleminggatan, DL180 is generally lower in WT than between, while Norrlandsgatan and Odengatan have very similar dust loads in both surfaces. Folkungagatan has similar dust loads some seasons and tendencies to higher dust load in WT in other seasons.

The difference in dust load in WT in Folkungagatan between the first season and the following seasons is due to the above-mentioned change in sampling area. Another feature at Folkungagatan is the marked increase in DL180 during the last season (2016–2017). This is due to repaving the street with a wear resistant stone mastic asphalt containing porphyry rock aggregates, but also with a coarse macro texture (determined by visual inspection) with high capacity to store dust.

Long term trends in the data differ from street to street, but the Sveavägen sites and Hornsgatan seem to have increasing dust amounts since 2014. Both Sveavägen sites show increasing dust amounts in both WT and BWT. In Hornsgatan, WT seems unaffected, while BWT increases. In Norrlandsgatan, the trend is less obvious.

A statistical view of the data (Fig. 6) from each surface reveal that WT of Fleminggatan, Norrlandsgatan and Sveavägen, together with BWT on Norrlandsgatan have similarly low dust loads, with small variation, while WT on Hornsgatan as well as BWT on Fleminggatan and Hornsgatan stands out with high dust loads and large variability. Folkungagatan DL180 data must be separated in time, since the sampling site was changed, and a new pavement was built in summer 2016 on the site as mentioned above (Fig. 6).

3.2. Small scale spatial road dust variability

Not only does the dust load vary between streets and during the season, the small-scale variation across a street can also be very high. In Fig. 7, ten WDS transects, sampled 2 h and about 20 cm apart at Fleminggatan, have been used to illustrate the variation in dust load. In the driving lane the wheel tracks are easily identified as even surfaces with low dust load (below 50 g/m2). Between wheel tracks and between the lanes are areas with higher dust loads, about 50–100 g/m2. Outside the lane, towards the kerb, the gradient is steep to high dust loads in the

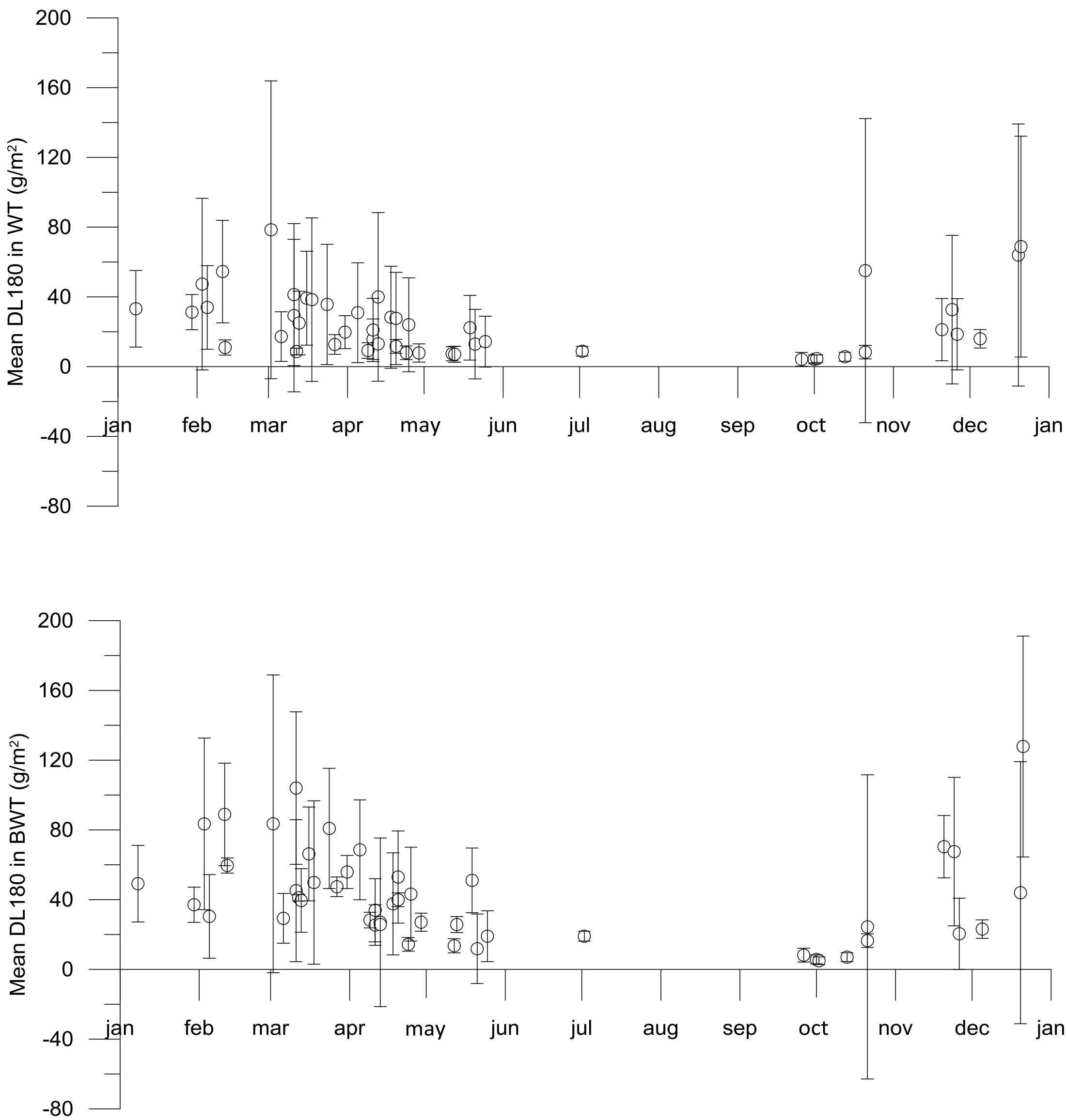

Fig. 4. Mean road dust load (DL180) in WT and BTW for seven locations in central Stockholm between 2011 and 2017. Error bars are standards deviations.

bicycle lane and parking area, up to about 300 g/m2. The large variation in the x direction outside the driving lane can both relate to temporal variation and to small-scale differences between the transects. Since WDS cleans each sampling surface, the exact same surface cannot be re-used in the following transect but have been moved up-stream to the traffic, not to be affected by water smearing by traffic.

3.3. *Size distributions and amount of dust < 10 μm*

The fraction of road dust being smaller than 10 μm (DL10) is of interest since it can be expected to contribute directly to airborne PM10 through suspension. In Fig. 8, cumulative size distributions of DL180 sampled on 2017-02-02 is shown. These distributions are typical for the high road dust load season and the shape is generally similar between streets. Nevertheless, the percentage smaller than 10 μm can be quite different. In Table 2, the percentage for the streets in Fig. 8 is shown and range from 14 to 18% of DL180. In all BTW samples during the six seasons, the percentage range from 2 to 30%, with a mean value of 14%. The percentage of DL10 is generally higher in winter and early spring.

Mean values of DL10 in BWT between the seasons 2011–2017 is shown in Fig. 9. Similar to the DL180 load, the DL10 fraction generally has a seasonal pattern with lower amounts in early autumn and late spring and a maximum in midwinter and early spring and range from about 20 mg/m2 in the generally low dust load in September to almost 90 g/m2 during the dustiest period in March.

3.3.1. *Macro texture influence on dust load*

In Fig. 10, macro texture (MTD) in and between wheel tracks on four streets have been plotted to road dust load (DL180) for six winter seasons from 2011 to 2017. Even though other factors affect the dust load, like traffic amount, speed and composition, meteorology and different suspension in and between wheel tracks, there is a clear tendency that coarser texture is related to higher dust load. Except for the exceptionally coarse macro texture in the Folkungagatan wheel track (over 2 mm), the macro texture in wheel tracks are lower than between wheel tracks. Within each functional section (in and between wheel tracks) there is also a trend with higher dust load at coarser macro texture. The new pavement at Folkungagatan (from mid-2016) is not included in the figure due to lack of macro texture data. Visually, it has a high texture, which also is reflected in high dust loads (see Fig. 5). One should keep in mind that texture was only measured once at each site. Therefore, the variation along the MTD axis in Fig. 10 would likely be higher if texture was available for each measurement occasion.

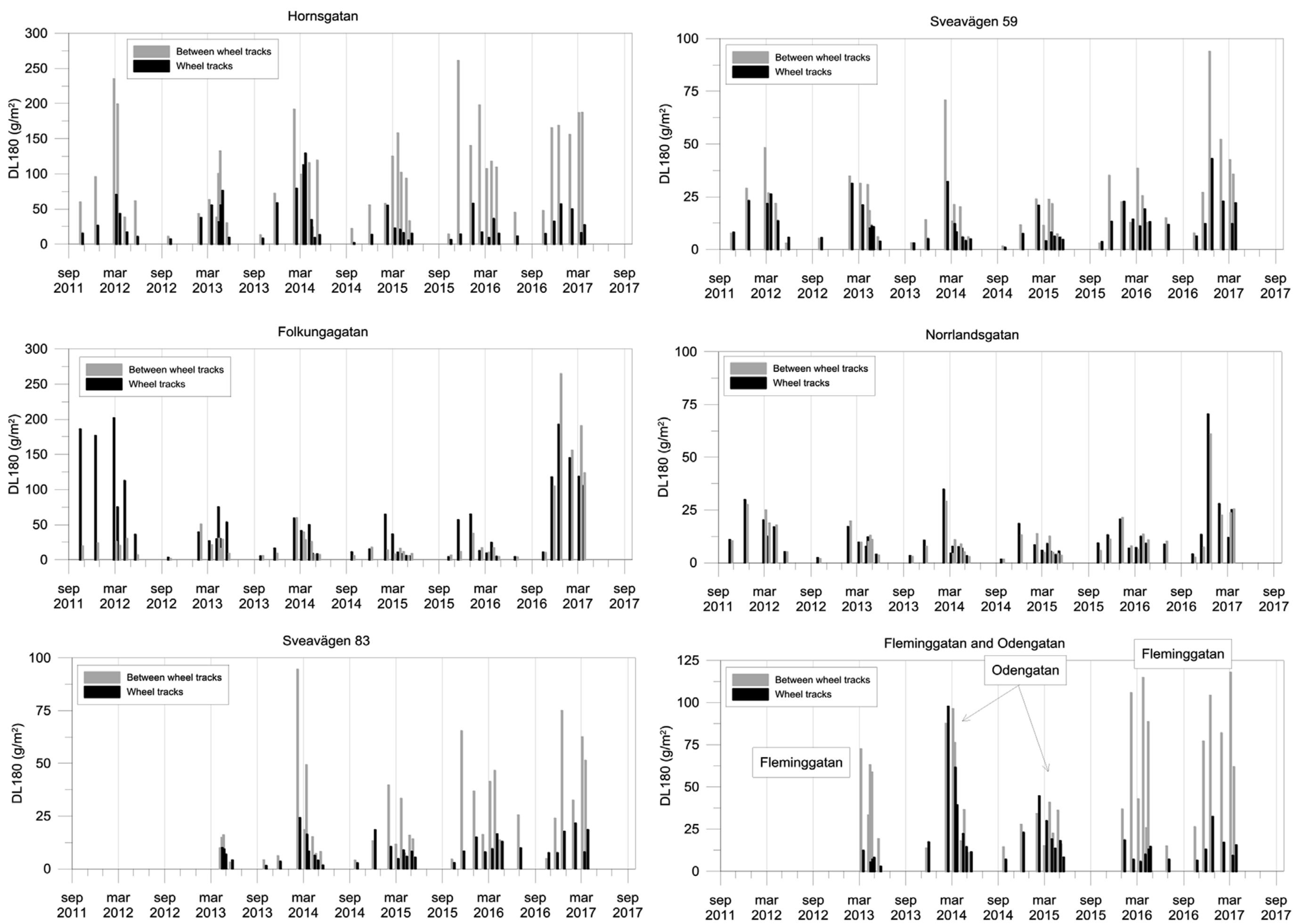

Fig. 5. Road dust load (DL180) variation during September to May between 2011 and 2017 in seven locations on Stockholm streets.

Measurements in wheel track on roads with similar pavement but higher speeds indicate that macro texture might vary with about 10% over a year, with the highest values after the studded tyre season and the lowest just before (Lundberg, 2012). Pavements at the measurement sites were not changed during these years, though, why texture values are likely to be representative.

4. Discussion

Based on available literature, the data set on both annual cycles of road dust load and the road dust cross-sections presented in this work are unique data sets. The annual cycle is a result of growing dust sources as well as increasing dust retention processes during autumn and winter. In spring the opposite circumstances reduce the dust load. Generally, dust load is higher between wheel tracks, than in wheel track, which is a result of the suspension caused by passing wheels. This difference is especially obvious in Fleminggatan, due to track bound traffic in one single narrow lane with a no-crossing line to the left and a bicycle lane to the right. Remaining streets have two lanes in each direction, resulting in more lane shifting that will affect the distribution of dust across the street. Norrlandsgatan is the street with least differences in and between wheel tracks, probably resulting from being a short link were cars often shift lanes at low speeds before a crossing with traffic lights. The size distribution of DL180 is generally rather similar between streets. Therefore, DL180 dust load is reflected in the DL10 dust load.

The influence of macro texture of the pavement on road dust load is obvious, with generally higher dust loads with coarser macro texture. Dry road dust sampling methods have shown an inverse relationship between macro texture (MTD) and suspendible dust load (Blomqvist et al., 2013; China and James, 2012; Panko et al., 2013; Padoan et al., 2018) which is a result of a higher capacity to store and retain dust at coarser macro textures. Even though only visual observations are available for the texture of the new pavement on Folkungagatan, the obvious increase in dust load has been followed by a likewise obvious drop in PM10 concentrations at the site. This indicates a reduced suspendible road dust emission, even though traffic increased during the same period. On the other hand, the mean speed in the lane decreased by 7 km/h due to a new bus stop (Elmgren, 2018). A high dust load can reflect strong sources, which is likely not the case with the wear resistant porphyry pavement on Folkungagatan, but also low suspension, which is promoted by coarse texture and low suspension forces. In Folkungagatan, dust sources should be comparably weak, while texture is deep and the suspension likely to be lower due to lower traffic speed than before the traffic shift. Weak sources causing slow accumulation in a rough texture with low suspension from traffic could therefore be hypothesized to explain the combination of high dust load and low PM_{10} on Folkungagatan. Of the total dust load sampled, the fixed dust load is high, while the suspendible load is low.

The WDS sampling in this study samples both suspendible and fixed dust load, i.e. the total dust load. At a certain location with a site-specific pavement surface macro texture and traffic conditions, the fixed load is likely to have a small variation, which was shown by China and James (2012). The results of this study, showing that the total dust load increases with coarser macro texture, could be explained by assuming that of the dust supplied to the surface, a higher proportion will

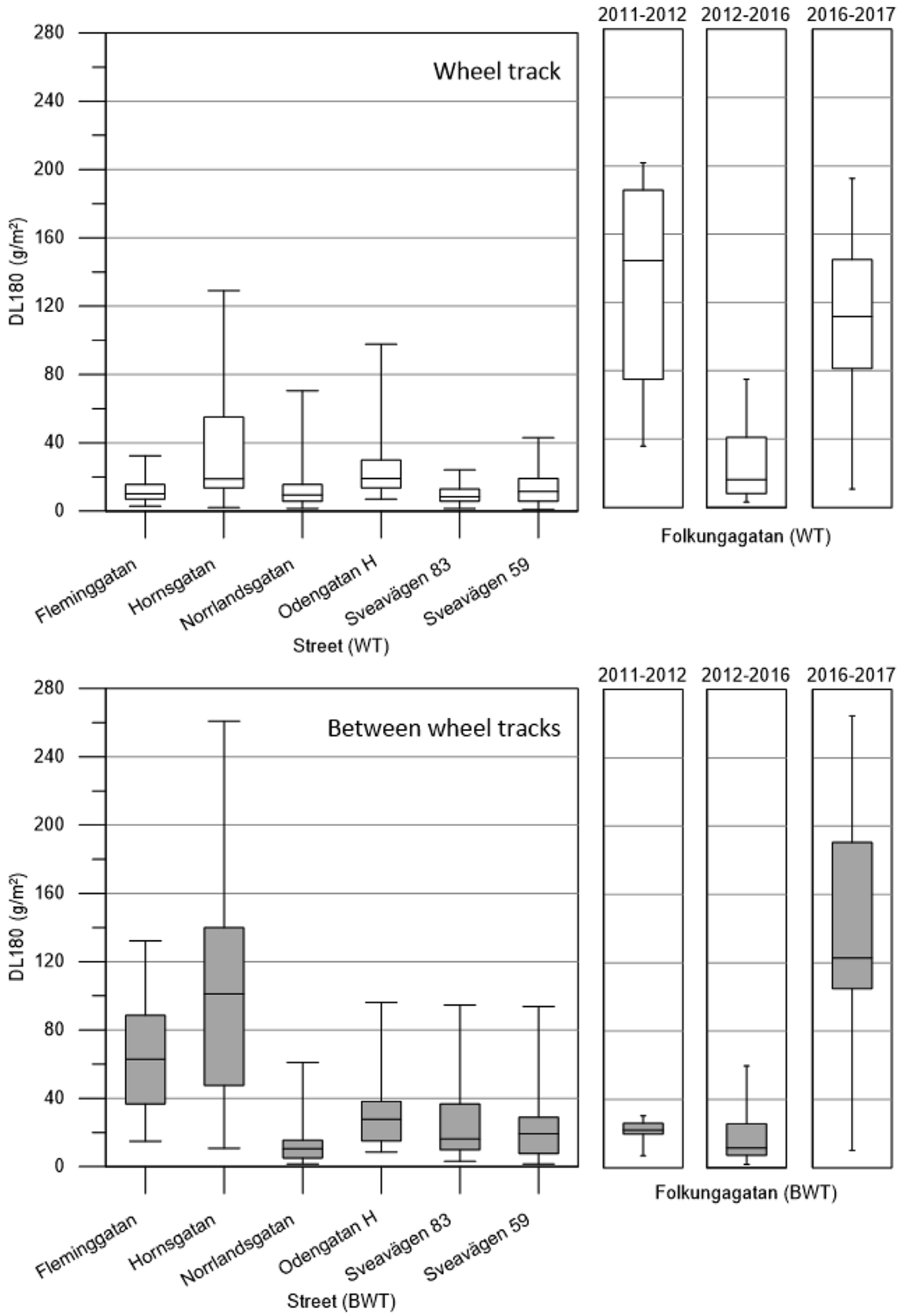

Fig. 6. Statistics for each surface 2011–2017. Plots show median, lower quartile, upper quartile, maximum and minimum values. The three rightmost bars in each figure show statistics for surfaces on Folkungagatan, where the sampling site and the pavement have been changed. In 2011–2012, the WT site was damaged with lost aggregates and cracks, in 2012–2016 both surfaces were in good condition and in 2016–2017 the street got a new pavement with higher macro texture.

become fixed with increasing texture depth. The suspendible dust load is influenced by direct action and turbulence from wheels and vehicles. The traffic characteristics (speed, amount, composition) in a street is therefore governing the maximum suspension depth. The fixed load is influenced by deposition and compaction and its upper level determined by the suspension depth. Since turbulent forces decrease rapidly from the surface, the assumption that the proportion of dust that is fixed will increase faster is reasonable, but still a speculation. A hypothetic model of this reasoning is described in Fig. 11.

The cross-street dust load variability described in this work shows that wheels, also at rather low speeds (30–50 km/h) in the central city, are effective dust suspenders. Wheel tracks generally have low dust loads. It can be argued that the emission from these surfaces during dry conditions is mostly direct wear from pavement and tyres. Dust accumulation will occur when wheel tracks are humid (Amato et al., 2012) and will result in suspension of dust at dry-up. In-between wheel tracks suspension from vehicle turbulence will be the dominant emission process. The traffic intensity and speed in the street will affect the amount remaining on the surface. Amato et al. (2017) showed that the suspendible dust load will decrease with increasing traffic intensity and that the relationship levelled out already at 1500 vehicles per lane and day. This relation might well be site specific, though, depending on road surface and traffic properties.

The dust load is expressed as DL180, meaning the surface concentration of dust smaller than 180 µm. The only directly comparable results are from the similar Chinese version of the WDS. This WDS is

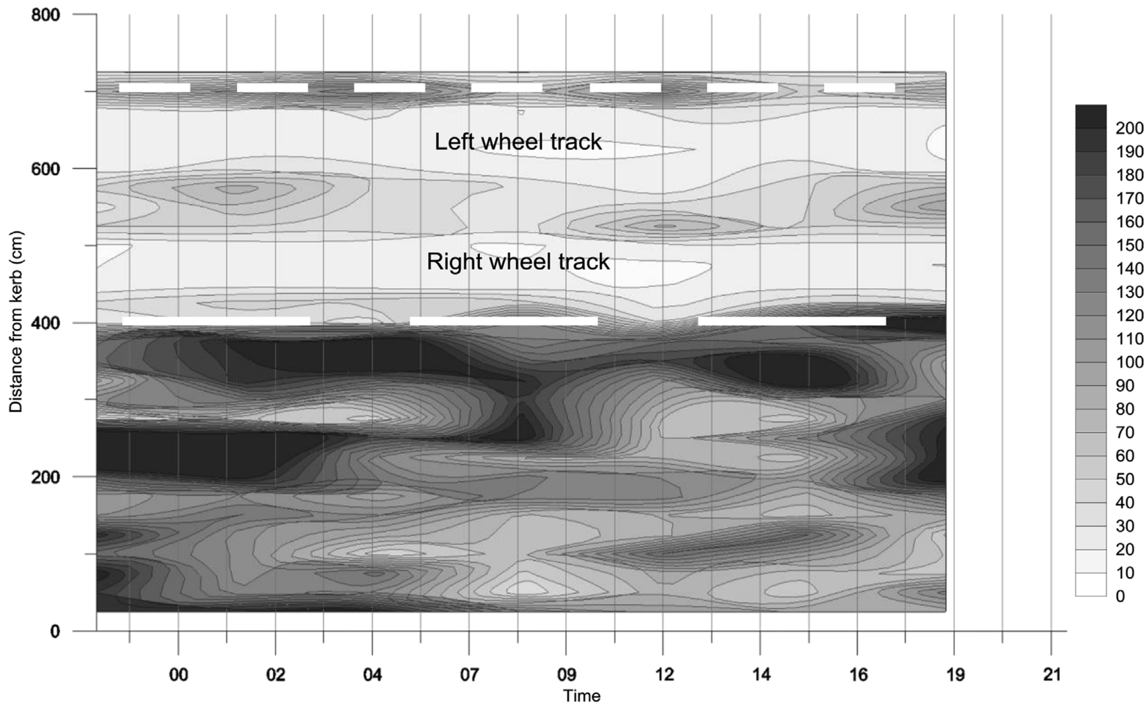

Fig. 7. Road dust load from kerb across parking area and driving lane during 21 h. Built from 10 transects with about 2 h apart.

inspired by the VTI WDS used in this paper but differs in some technical dimensions and specifications. In Huang et al. (2017), DL180 of Beijing streets vary between 28 and 117 g/m^2, which is within the range of the dust loads found in Stockholm. The dust sources are partly different in Beijing and Stockholm and there is no information on the pavement and traffic properties from the Beijing data. Therefore, further comparison is not possible.

The most commonly used dust load unit for similar studies is silt load (sL), based on the method used in the US EPA emission model AP-42 (EPA, 2002). Silt load is defined as particles smaller than 75 µm on the road surface. Using the cumulative size distributions of DL180, the

Table 2
Percentage of DL180 smaller than 10 µm from sampling 2017-02-02.

Street	< 10 µm (%)
Fleminggatan	17
Folkungagatan	18
Hornsgatan	17
Norrlandsgatan	13
Sveavägen 83	15
Sveavägen 59	14

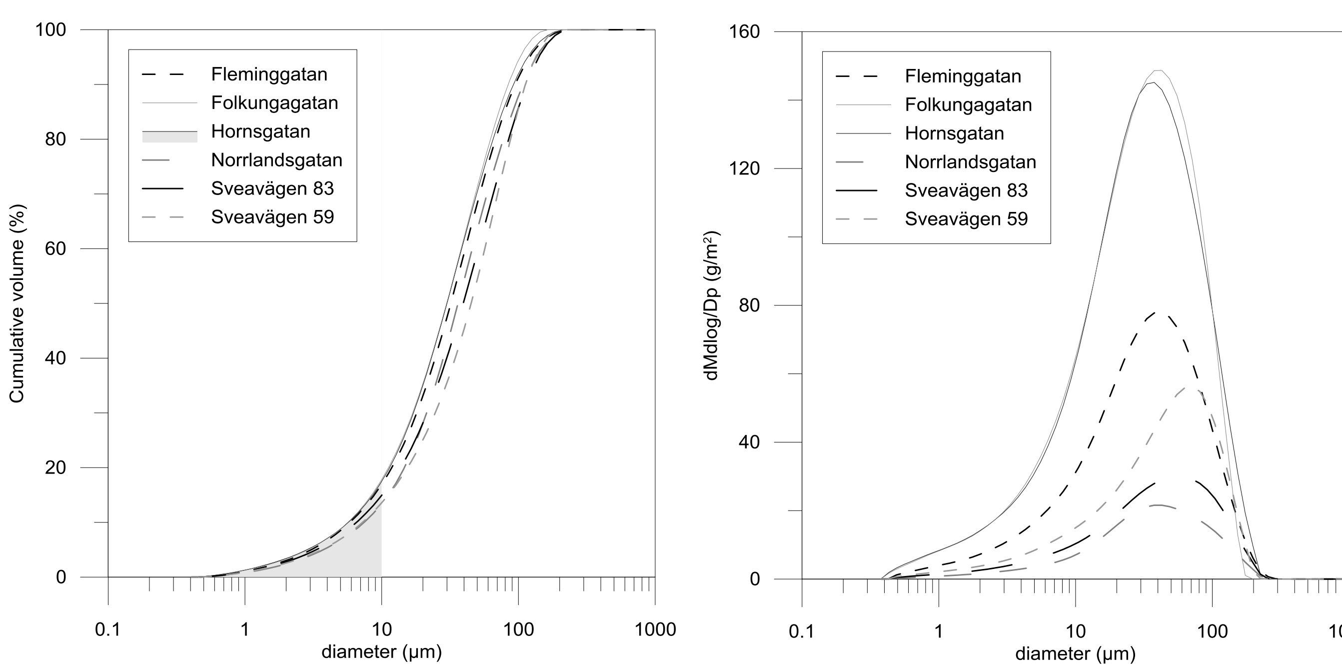

Fig. 8. Examples of cumulative (left) and frequency based (right) mass size distributions in DL180 samples from Stockholm streets in 2017–02-02. Percentage used for DL10 calculation marked with grey.

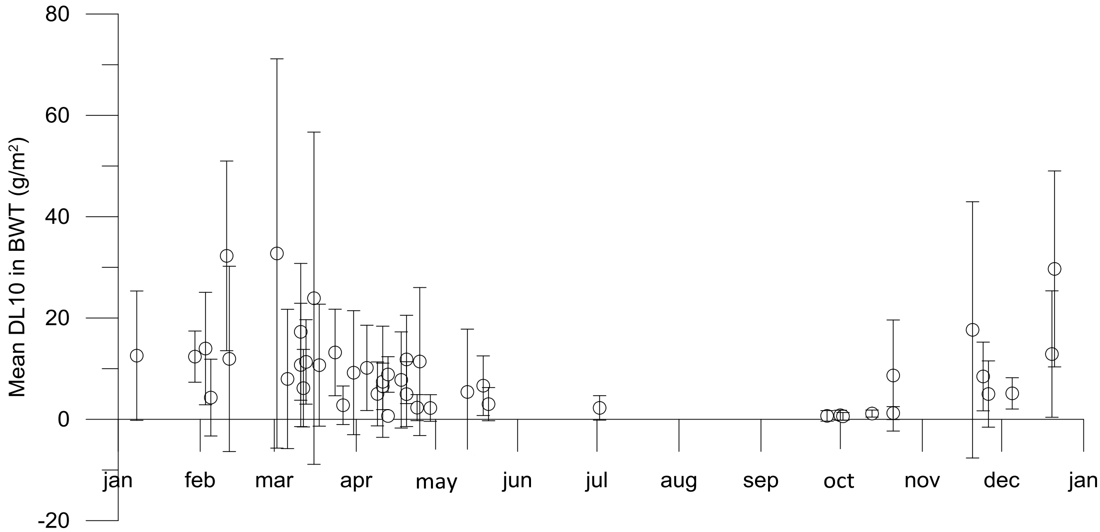

Fig. 9. Mean road dust load (DL10) in BWT for seven locations in central Stockholm between 2011 and 2017. Error bars are standard deviations.

fraction closest to silt load (< 76 μm) can be calculated. Silt load for all streets was calculated from DL180 for the season 2015–2016 and ranges from 2.5 to about 250 g/m2, which can be compared to the recommended default silt loading values for public paved roads of AP-42 of 0.1–3 g/m^2. At industrial facilities, AP-42 suggests silt load up to 400 g/m^2 (EPA, 2006). It should be noted though, that the silt load estimation technique used in the AP-42 method, is based on dry brushing and vacuuming of the road surface. This technique might not be as efficient in removing dust from the surface as the high-pressure water cleaning used in WDS Therefore, silt loads could be expected to be lower. Also, a part of the explanation for the large differences, is that the US streets that AP-42 is developed for are very different from Swedish streets in winter and spring, where dust sources are likely to be much stronger.

A similar dry sampling technique as used in AP-42, which has been used rather extensively, is the technique developed by Amato et al. (2009). The dust amount sampled by a dry vacuum cleaning method will sample the mobile dust that is available for the suction force applied, which depends on effect of the vacuum cleaner, the nozzle design and how the nozzle is operated. It will also be affected by the humidity of the road surface, which is one of the main reasons why the WDS is operating with water. In Sweden, humid, wet or even snowy or icy road surfaces are common, and a dry method would be hard to apply in many situations. On the other hand, suspending road dust in water will dissolve some particles that might contribute to airborne PM10 and affect the size distribution of the dust.

If assuming the dry sampler of Amato et al. (2009) collects all available road dust PM10, the dust load smaller than 10 μm (DL10) calculated in this work can be compared to the PM10 dust load. Amato et al. (2013) found that the PM10 dust load was 2–22 mg/m2 depending on location. In our data, DL10 range from 21 to 9000 mg/m2, indicating that the dustiest street in the study by Amato et al. (2013) is similar in dust load to the cleanest street in the current study. Even though streets in Nordic conditions are likely to be much dustier due to

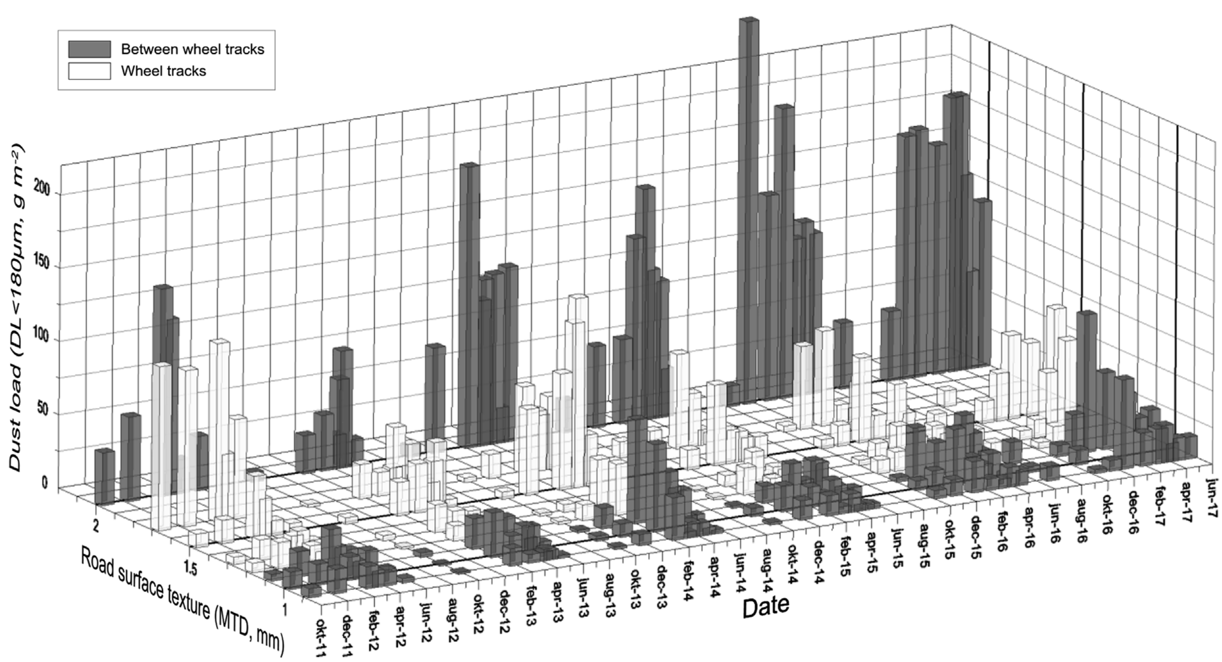

Fig. 10. Influence of road surface texture (MTD) on road dust load (DL180) between 2011 and 2017. Note that the new pavement on Folkungagatan is not included, due to lack of texture data (see text).

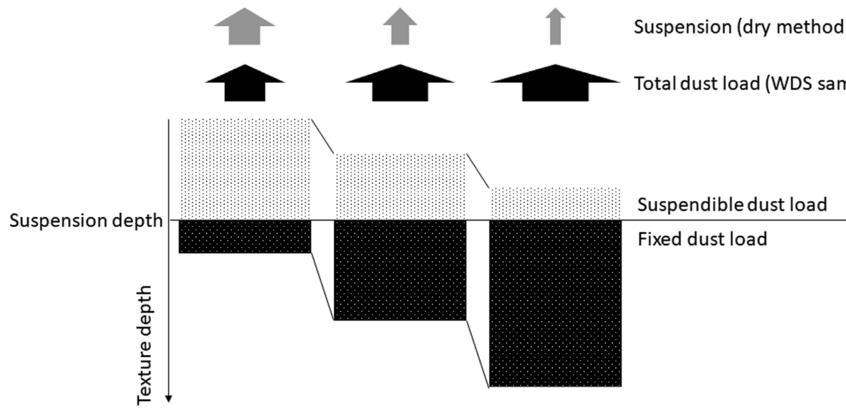

Fig. 11. Hypothetical model of relation between texture, suspendible and fixed dust load.

studded tyres and winter sanding, this comparison should be made with caution, since the aerosol PM10 cut-off is likely not directly comparable to the below 10 µm fraction in a cumulative size distribution in water. Also, it is likely that this difference is partly a result of the difference in sampling the suspendible fraction (dry method), and the total dust load (wet method). A factor complicating the comparison between the DL180 dust load value and dry vacuuming samplers is that the WDS is used in the Nordic countries Sweden, Norway and Finland, with high dust loads, while the dry vacuuming samplers are used in mid and southern Europe, where the dust load is generally lower. An intercomparison of different samplers in the same streets should be beneficial to better understand the differences.

In Stockholm, PM10 is monitored in several places using mainly TEOM (for details see website of SLB-analys: http://www.slb.nu). One might expect PM10 concentrations in the city to be directly depending on the dust load, but a number of other factors affect this relationship, as described in Fig. 12. Two main sources contribute to road dust emissions: direct emissions from road surface wear and suspension of accumulated dust. The strength of the dust sources increases in late autumn, as studded tyre frequency increases as do occasions when sand and salt is used for traction control. Simultaneously, the frequency of wet or humid road surfaces, binding dust to the surface, increases. The local contribution to PM10 starts to rise in the autumn but is dampened by the more frequent wet surfaces. Road dust accumulates during these conditions but as the frequency of wet road surfaces decrease in spring, the accumulated dust starts to be suspended by traffic, causing high PM10 peaks. As the dust sources decrease and the road dust load is depleted, its contribution to PM10 decreases.

As obvious in the discussion above, there is a need for harmonization in road dust sampling techniques, what parameters to study and more knowledge on their influence on air quality and the road dust system. Road dust load has an obvious influence on air quality, but the processes involved are many and the system complex. The currently most comprehensive road dust emission model, NORTRIP (Denby and Sundvor, 2012), describes many of these processes in detail and has been shown to describe PM10 emission and concentration with reasonable to high accuracy (e.g. Denby et al., 2013a,b; Kauhaniemi et al., 2014), taking account for meteorology, traffic, surface moisture, pavement wear and road operation measures.

All road dust sampling methods have pros and cons and could possibly complete each other. Being a young research area, these issues will hopefully be addressed in coming years. Road dust is certainly in many environments an important source for PM10 with a complex dependence on source contributions and meteorology as well as road surface and traffic properties, resulting in an array of mitigation possibilities in need of a scientific basis for optimal performance.

5. Conclusions

From this work is concluded that:

- There is a seasonal dependency in road dust loads in Stockholm, with a build-up in autumn, maximum loads in mid-winter to early spring and low values in late spring and autumn.
- The road dust load, expressed as DL180, varies from about 15 to 200 g/m2.

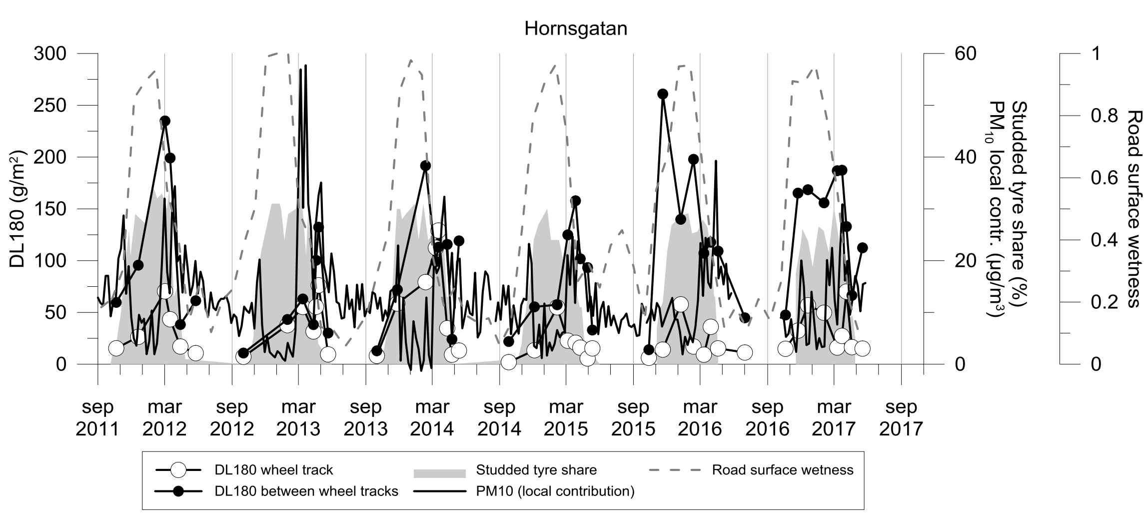

Fig. 12. Six seasons in Hornsgatan, Stockholm showing dust load (DL180), local contribution to PM_{10}, studded tyre frequency and road surface wetness.

- The lateral variation is high with typically large dust loads in between and outside wheel tracks and low in wheel tracks.
- The percentage of DL180 which is below 10 µm (DL10) and therefore directly, through suspension, could contribute to PM10, varies from 2 to 30%, with a mean value of 14%.
- In average, DL10 follows the same seasonal cycle as DL180 with high loads in mid-winter to early spring and low values in late spring and autumn. The DL10 percentage of DL180 is generally highest in midwinter and early spring and lower in autumn and late spring.
- Road dust load is depending on road surface properties, where higher macro texture increases dust loads.
- Repaving of one of the streets resulted in markedly increased dust loads, but also reduced PM_{10} concentrations, indicating a growth of the fixed dust load but a reduction in suspendible dust load due to high macro texture.
- A comparison between DL180 and silt load results in that the Stockholm streets have silt loads comparable to values suggested for industrial sites in AP-42, which is likely a result of more effective sampling using the WDS technique compared to the whisk broom and dustpan used for silt load sampling as well as a result of large differences between Swedish and north American dust sources and road conditions.
- Road dust load is an important source for high PM10 concentrations, but the relation is affected by many factors, the main one being road surface humidity. The highest PM10 concentrations appear at high dust loads and dry roads in late winter and early spring.
- The wet dust sampler (WDS) is a useful tool for total dust load follow-up studies in most climates and weather conditions and opens up for a range of sample analyses connected to sources and road operation activities. Sampling of the suspendible fraction requires other techniques, though.

Declaration of interests

None.

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